

Radio ejection in the evolution of X-ray binaries: the bridge between low mass X-ray binaries and millisecond pulsars

Luciano Burderi, Francesca D'Antona

Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio Catone (Roma), Italy

Tiziana Di Salvo

Astronomical Institute "Anton Pannekoek," University of Amsterdam, Kruislaan 403, NL 1098 SJ Amsterdam, the Netherlands

Marta Burgay

Università di Bologna, Dipartimento di Astronomia, via Ranzani 1, 40127 Bologna, Italy

We present a scenario for the spin-up and evolution of binary millisecond pulsars. This can explain the observational properties of the recently discovered binary millisecond pulsar PSR J1740-5340, with orbital period 32.5 hrs, in the Globular Cluster NGC 6397. The optical counterpart of this system is a star as luminous as the cluster turnoff stars, but with a lower T_{eff} (a larger radius) which we model with a star of initial mass compatible with the masses evolving in the cluster ($\simeq 0.85 M_{\odot}$). This star has suffered Roche lobe overflow while evolving off the main sequence, spinning up the neutron star to the present period of 3.65 ms. There are evidences that at present, Roche lobe overflow is still going on. Indeed Roche lobe deformation of the mass losing component is necessary to be compatible with the optical light curve. The presence of matter around the system is also consistent with the long lasting irregular radio eclipses seen in the system. We propose that this system is presently in a phase of 'radio-ejection' mass loss. The radio-ejection phase can be initiated only if the system is subject to intermittency in the mass transfer during the spin-up phase. In fact, when the system is detached the pulsar radio emission is not quenched, and may be able to prevent further mass accretion due to the action of the pulsar pressure at the inner Lagrangian point.

1 Introduction

The widely accepted scenario for the formation of a millisecond radio pulsar (hereafter MSP) is the recycling of an old neutron star (hereafter NS) by a spin-up process driven by accretion of matter and angular momentum from a Keplerian disc, fueled *via* Roche lobe overflow of a binary late-type companion (see Bhattacharya & van den Heuvel 1991 for a review). If the NS has a magnetic dipole moment (typical values are $\mu \sim 10^{26} - 10^{27} \text{ G cm}^3$) the disc is truncated at the magnetosphere, where the disc pressure is balanced by the magnetic pressure, P_{MAG} , exerted by the NS magnetic field. Once the accretion and spin-up process ends, the NS is visible as a MSP. Indeed, a common requirement of all the models of the emission mechanism from a rotating magnetic dipole is that the space surrounding the NS is free of matter up to the light cylinder radius R_{LC} (at which the speed of a body rigidly rotating with the NS equals the speed of light)

An interesting evolutionary phase can occur if the mass transfer rate drops below the level required to allow the expansion of the magnetosphere beyond R_{LC} , switching-on the emission

from the rotating magnetic dipole (e.g. Illarionov & Sunyaev, 1975; Ruderman, Shaham & Tavani 1989; Stella et al., 1994). The pressure exerted by the radiation field of the radio pulsar may overcome the pressure of the accretion disk, thus determining the ejection of matter from the system. Once the disk has been swept away, the radiation pressure stops the infalling matter as it overflows the inner Lagrangian point.

2 The Effects of the Pulsar Energy Output

The push on the accretion flow exerted by the (assumed dipolar) magnetic field of the NS can be described in terms of an outward pressure (we use the expressions outward or inward pressures to indicate the direction of the force with respect to the radial direction) exerted by the (assumed dipolar) rotating magnetic field, B , on the accretion flow: $P_{\text{MAG}} = \frac{B^2}{8\pi} = 7.96 \times 10^{14} \mu_{26}^2 r_6^{-6} \text{ dy/cm}^2$, where μ_{26} is the magnetic moment of the NS in units of 10^{26} G cm^3 , and r_6 is the distance from the NS center in units of 10^6 cm . Another contribution to the outward pressure is given by the radiation pressure (if present) generated by the rotating magnetic dipole, which, assuming isotropic emission, is given by: $P_{\text{RAD}} = 2.04 \times 10^{12} P_{-3}^{-4} \mu_{26}^2 r_6^{-2} \text{ dy/cm}^2$. The accretion flow, in turns, exerts a inward pressure on the field: for a Sakura–Sunyaev accretion disc in zone C (certainly the case at large radii), the pressure is dominated by the gas contribution, $P_{\text{DISC}} \propto \dot{M}^{17/20} r^{-21/8}$, where \dot{M} is the accretion rate (see e.g. Frank, King & Raine 1992). This inward ram pressure of the accretion flow equals the outward pressure due to the magnetic dipole at the magnetospheric radius that defines an equilibrium point. Since the radial dependence of the magnetostatic pressure exerted by the NS is steeper than the radial dependence of the disc pressure, the equilibrium point defined above is stable inside R_{LC} , where the pulsar radiation pressure P_{RAD} is absent. On the other hand, the equilibrium point is unstable beyond R_{LC} . Therefore if P_{RAD} dominates over P_{DISC} for any $r > R_{\text{LC}}$ the whole accretion disc is swept away up to the inner Lagrangian point L_1 by the radiation pressure of the pulsar. During this “radio ejection” phase, the mechanism that drives *mass overflow* from L_1 can well be active, but *the pulsar radiation pressure at L_1 prevents mass accretion onto the NS* (see Burderi et al. 2001).

It is possible that mass transfer during the binary system evolution suffers instabilities, due to the X-ray illumination of the secondary star during the accretion phases, which makes the mass transfer rate quite unsteady. In this case the system temporarily detaches, allowing the pulsar to switch-on. However the companion evolution, which leads to radius expansion, will lead again to overflow. Mass transfer to the NS and spin-up, due to the accretion of angular momentum of the mass overflowing the Roche lobe can therefore go on, until the pulsar has been so much spun up that its radiation pressure at the inner Lagrangian point is high enough to prevent mass accretion. In this case we expect to be in the presence of a radio MSP which from time to time is obscured by the matter floating around the system.

3 PSR J1740-5340

The eclipsing MSP PSR J1740-5340, discovered by D’Amico et al. (2001a) in the globular cluster NGC 6397, has the longest orbital period ($P_{\text{orb}} \simeq 32.5 \text{ hrs}$) and the most massive minimum companion mass ($0.18 M_{\odot}$) among the 10 eclipsing pulsars detected up to now. The spin period ($P_{\text{spin}} \simeq 3.65 \times 10^{-3} \text{ s}$) and its derivative ($\dot{P}_{\text{spin}} = 1.59 \times 10^{-19}$), recently derived by D’Amico et al. (2001b), allow the determination of the NS magnetic moment, $\mu_{26} \simeq 7.7$. Its position with respect to the cluster center excludes the possibility of a contamination of \dot{P}_{spin} due to the NS acceleration in the gravitational field of the cluster (D’Amico et al. 2001b), implying that the estimate of the NS magnetic moment is reliable. The optical counterpart of PSR J1740-5340, identified by Ferraro et al. 2001 with a slightly evolved turnoff star in the sample studied by

Taylor et al. (2001) using data from the HST archive, also shows light modulation at the same orbital period as the radio data (Ferraro et al. 2001).

PSR J1740-5340 shows radio eclipses lasting for about 40% of the orbital phase at 1.4 GHz (D’Amico et al. 2001b). Out of eclipse the pulsar signal at 1.4 GHz shows significant excess propagation delays (up to ~ 3 ms) and strong intensity variations. This suggests that in PSR J1740-5340 the signal is propagating through a dense material surrounding the system. In order to investigate this possibility, D’Amico et al. (2001b) have fitted the excess delays measured in two adjacent bands of 128 MHz each at 1.4 GHz. They found that the excess delays Δt can be well fitted with the equation $\Delta t \propto \nu^{-2.02 \pm 0.30}$ that strongly supports the hypothesis that the responsible mechanism is dispersion in a ionized medium (see Fig. 1, right panel). In this case the corresponding electron column density variations are $\Delta n_e \sim 8 \times 10^{17} \Delta t_{-3} \text{ cm}^{-2}$, where Δt_{-3} is the delay at 1.4 GHz in ms. For $\Delta t_{-3} \sim 3$ the estimated electron column density is $\sim 2.4 \times 10^{18} \text{ cm}^{-2}$.

The eclipsing radius of the system is $R_E \sim 4.4 \times 10^{11} \text{ cm}$ (D’Amico et al. 2001b), taking $m_1 = 1.8M_\odot$ for the NS mass and $m_2 = 0.45M_\odot$ for the secondary mass (see below) and $P_{\text{orb}} \sim 32.5 \text{ hr}$. This radius is larger than the Roche lobe radius of the secondary ($\sim 1.3 \times 10^{11} \text{ cm}$). This means that the eclipsing matter is beyond the gravitational influence of the companion star and must be continuously replenished. From a simple calculation (see Burderi et al. 2002 for details), we can estimate a rough order of magnitude of the necessary mass loss rate from the secondary, \dot{M} , by assuming spherical symmetry (which is, however, not consistent with the randomly variable signal intensity shown by the radio data). We find \dot{M} up to $\sim 0.6 \times 10^{-10} M_\odot \text{ yr}^{-1}$. Even considering the uncertainty on this estimate, winds induced by the pulsar radiation are typically 2–3 orders of magnitude weaker (Tavani & Brookshaw, 1991). It is also unlikely that this matter is provided by the wind from the main sequence companion star, given that the mass loss rate due to the star wind is expected to be less than $\sim 10^{-12} M_\odot \text{ yr}^{-1}$. We conclude that the mass loss rates we derive are more consistent with Roche lobe overflow driven by nuclear evolution of the secondary and orbital angular momentum mass loss, than with a possible wind from the secondary.

We propose that this system is now experiencing the radio ejection phase postulated above. When: i) as a result of the accretion of matter and angular momentum, the NS spin period is so short that, potentially, the radiation pressure of a pulsar phase would be high enough to overcome the pressure of the matter overflowing the Roche lobe, and ii) the oscillations in \dot{M} are large enough to allow the MSP to switch-on, then the radio-ejection phase begins, leading to the appearance of the system as it looks now.

4 Binary Evolution in the Globular Cluster NGC 6397

In order to choose coherently the input parameters for the possible evolution leading to PSR J1740-5340, it is important to take into account what we know of the general properties of the host cluster. Figure 1 (left panel) shows the composite HR diagram of NGC 6397 in the plane M_v versus $V - I$. The open circles identify the objects examined by Taylor et al. (2001) in the core of this cluster, to select objects which have been probably subject to binary evolution. One of the Taylor et al. (2001) BY Dra candidates, plotted as a full dot in Figure 1 (left panel), is indeed the optical counterpart of PSR J1740-5340. On the observational HR diagram we show an isochrone of 12 Gyr for metallicity in mass fraction $Z=0.006$ and helium mass fraction $Y=0.23$. The isochrone of 12 Gyr, which fits the cluster HR diagram, implies that a mass of $\sim 0.81 M_\odot$ is evolving at the cluster turnoff (TO), and that its TO luminosity is $\simeq 2.24 L_\odot$. Different interpretations of the HR diagram morphology, assuming that the distance of the cluster is smaller, may lead to values of the TO luminosity down $\sim 1.8 L_\odot$. The optical counterpart of PSR J1740-5340 is at a luminosity similar to the TO luminosity (i.e. $1.8\text{--}2.3 L_\odot$), but cooler

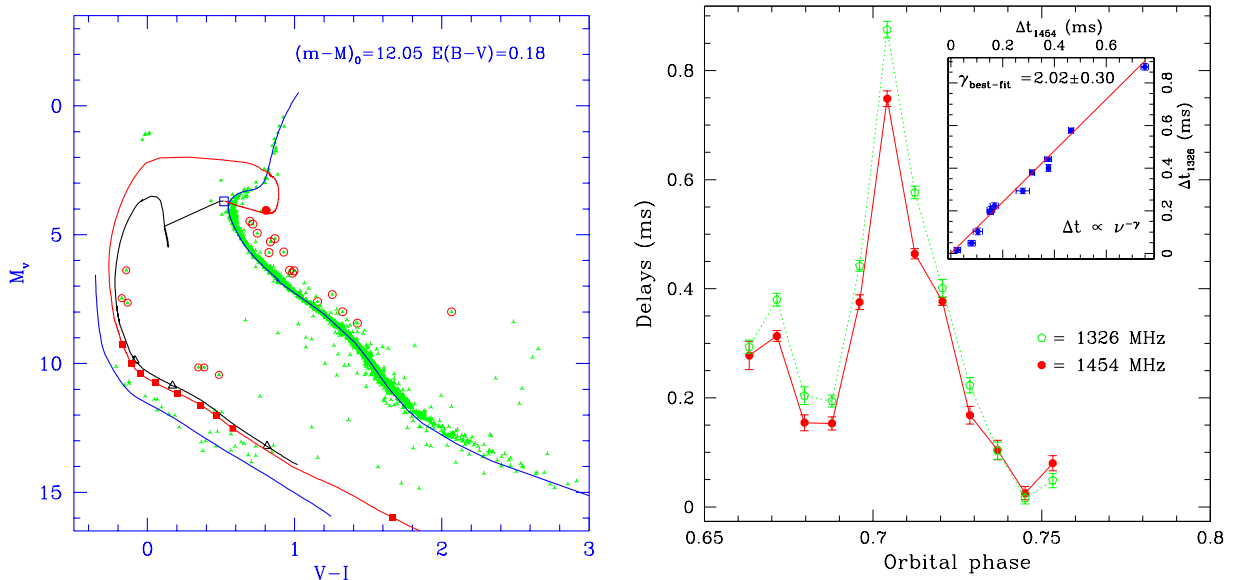


Figure 1: **Left:** HR diagram of the Globular Cluster NGC 6397, with an isochrone of 12 Gyr superimposed. Starting close to the turnoff at the open square, we show a standard evolution (case 2) of the companion of the NS, having an initial mass of $0.85M_{\odot}$ and an initial orbital period of 14.4 hrs (track evolving first towards the right of the figure, and passing through the observational counterpart of PSR J1740-5340 – full dot), and the evolution of case 3, which includes a fixed irradiation luminosity (track to the left). Both sequences end into the WD evolution of a $0.246 M_{\odot}$ (case 2) and $0.216 M_{\odot}$ (case 3). Both sequences are followed along the WD cooling, which is dominated by residual proton proton burning lasting for more than a Hubble time. Ages of 17, 20 and 26 Gyr are labelled as triangles along the cooling track of case 3. Ages from 13 to 20 in steps of 1 Gyr, plus a last point at 25 Gyr, are labelled as squares for case 2. **Right:** Excess propagation delays as a function of the orbital phase in PSR J1740-5340. The inset shows the best fit to these time delays.

than the TO, that is, at a radius larger than the TO radii.

We study four cases of evolution (see Fig. 1, left panel, and Burderi et al. 2002). In all cases, we model the initial parameter of the system as starting with a $0.85 M_{\odot}$ companion, a $1.4M_{\odot}$ NS, and a orbital initial period of 14.27 hr. We follow the binary evolution with the ATON1.2 code (D’Antona, Mazzitelli, & Ritter 1989). The mass loss rate is computed following the formulation by Ritter (1988), as an exponential function of the distance of the stellar radius to the Roche lobe, in units of the pressure scale height. This method also allows to compute the first phases of mass transfer, during which the rate reaches values which can be much larger than the stationary values, due to the thermal response of the star to mass loss. The evolution of the system also includes orbital angular momentum losses through magnetic braking, in the Verbunt & Zwaan (1981) formulation, in which the braking parameter is set to $f = 1$. We also tested a case in which $f = 2$.

When mass accretion on the NS is assumed, and the binary evolution suffers a Low Mass X-ray Binary (LMXB) phase, it is also important to consider how the X-ray phase would affect the binary evolution we are considering, as a fraction $R_2^2/(2a)^2 \leq 2.7 \times 10^{-2}$ of the X-ray luminosity impacts at the secondary surface. A self-consistent modelling is quite difficult, as the feedbacks are not easy to describe both physically and numerically. We follow a simplified schematization in which the star is immersed in the X-ray radiation bath, and the total luminosity L_{tot} which it must radiate is the sum of the stellar luminosity L_* plus the heating luminosity L_h , from which an ‘irradiation temperature’ $T_{irr} = (L_h/4\pi\sigma R_2^2)^{1/2}$ is defined. The stellar luminosity and T_{eff} then are related by: $L = L_{tot} - L_h = 4\pi\sigma R_2^2(T_{eff}^4 - T_{irr}^4)$. Consequently, the stellar T_{eff} becomes hotter due to the irradiation, and the star rapidly evolves in the HR diagram at a location

determined by the amount of irradiation allowed. The phases of mass transfer are only slightly altered by the new system conditions. However, as the star loses mass, its radius becomes larger than the radius of the standard sequence. This difference amounts to $\sim 20\%$ at the orbital period of PSR J1740-5340.

All the sequences are evolved until the mass loss phase finally ends with the stellar remnant evolving into the white dwarf region as low mass helium white dwarfs. We see that the most luminous three objects among those identified by Taylor et al. (2001) as helium WDs actually may be the end-products of such an evolution. The optical component of PSR J1740-5340 also seems compatible with the evolution we have suggested. It lies along case 2 evolution, that not including irradiation, as, in fact, the pulsar luminosity is not important as irradiation source for the binary.

4.1 The Evolution of the Progenitor System of PSR J1740-5340

As already said, the binary evolution which we are describing is not dramatically altered by the irradiation due to the LMXB phase: in particular, the final evolution is very similar, although the white dwarf remnant mass is slightly smaller. However, it helps to predict that the LMXB phases can be alternated with phases in which the system remains detached, as already had been suggested for systems having main sequence companions. We now consider the evolution of the system, taking also into account the pulsar's behavior. Any time the system detaches, the radio pulsar will switch on, but it will be quenched again when the mass transfer resumes. In the HR diagram the position of the secondary component will shift from its 'irradiated' position during the LMXB mass transfer phase (track 3 on the left of the MS) to its 'standard' position along track 1. However, as discussed in Burderi et al. (2001), when the pulsar is spinning sufficiently fast and the orbital period is sufficiently long (longer than a critical value $P_{\text{crit}} \propto P_{\text{spin}}^{9.6} \mu^{-4.8} \dot{M}^{2.04}$), the radiation pressure exerted by the pulsar at the inner inner Lagrangian point is larger than the pressure exerted by the matter overflowing the Roche lobe even if the mass transfer rate recovers its secular value dictated by the nuclear evolution of the companion. If $P_{\text{orb}} \geq P_{\text{crit}}$ the system will remain in the radio-ejection phase during all the subsequent binary evolution. In this case, the matter overflowing the Roche lobe will be accelerated by its interaction with the pulsar radiation and ejected from the system. In the case of PSR J1740-5340, the critical period P_{crit} to reach the 'radio-ejection' phase is ~ 39 hr, not very different from its orbital period. Thus, PSR J1740-5340 is possibly in the radio-ejection phase. Considering the dependency of P_{crit} from the system parameters, the fact that $P_{\text{crit}} \sim P_{\text{orb}}$ is compelling.

5 Summary and Conclusions

We have considered the evolution of possible progenitors of the binary MSP PSR J1740-5340 in the Globular Cluster NGC 6397. We can reproduce the HR diagram location of the optical companion, starting mass transfer to the NS from a hypothetical secondary of mass $0.85 M_{\odot}$, slightly evolved off the main sequence when mass transfer begins. In conclusion we propose that:

- i) Orbital evolution calculations shows that a slightly evolved $0.85 M_{\odot}$ secondary orbiting a NS can transfer mass to the NS, and reaches a stage in which its mass is reduced to $\simeq 0.45 M_{\odot}$, and its optical location in the HR diagram is then compatible with the recently detected optical counterpart of PSR J1740-5340;
- ii) PSR J1740-5340 might represent a system whose evolution has been envisioned by Burderi et al. (2001): the spin and the magnetic moment of the pulsar may keep the system in a radio-ejection phase in which accretion is inhibited by the radiation pressure exerted by the pulsar on the overflowing matter while the mechanism that drives the Roche lobe overflow from the

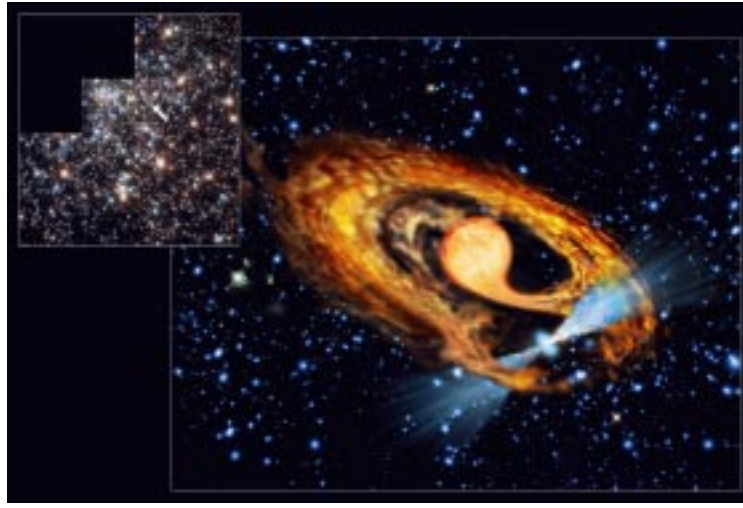


Figure 2: An artistic impression of the system PSR J1740-5340 based on the scenario proposed in this paper (courtesy of ESO).

companion is still active, thus causing an intense wind which would be very difficult to explain otherwise. This evolution seems to be the only viable possibility to explain the long lasting eclipses and the strong intensity variation randomly occurring in the radio emission. An artistic impression of the system, according to this scenario, is shown in Figure 2.

As a final remark we note that $P_{\text{orb}} \sim P_{\text{crit}}$ suggests the interesting possibility that this system could swiftly switch from the present radio pulsar phase to an accretion phase in which it should be visible as a $L_X \sim 10^{36}$ ergs s $^{-1}$ LMXB.

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